

# Evaluation of a Stirling Solar Dynamic System for Lunar Oxygen Production

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## **Abstract**

An evaluation of a solar concentrator-based system for producing oxygen from the lunar regolith was performed. The system utilizes a solar concentrator mirror to provide thermal energy for the oxygen production process as well as thermal energy to power a Stirling heat engine for the production of electricity. The electricity produced is utilized to operate the equipment needed in the oxygen production process. The oxygen production method utilized in the analysis was the hydrogen reduction of ilmenite. Utilizing this method of oxygen production a baseline system design was produced. This baseline system had an oxygen production rate of 0.6 kg/hr with a concentrator mirror size of 5 m. Variations were performed on the baseline design to show how changes in the system size and process rate effected the oxygen production rate.

## **Introduction**

The ability to produce oxygen is a key aspect of the successful human exploration and colonization of the lunar surface. Oxygen is required as a propellant reactant and is also needed to sustain a breathable atmosphere within habitation modules. Transporting oxygen from the Earth's surface is very costly and requires a sufficient stockpile to be housed on the lunar surface as a precaution in case there is a disruption with the supply from Earth. By producing the oxygen from material available on the lunar surface, the dependence on Earth re-supply and its cost can be eliminated. In addition to the cost savings, utilizing available resources to produce oxygen is the first step toward a viable self-sustaining human presence on the lunar surface.

Oxygen is the most prevalent element on the lunar surface. However, it is chemically locked up in various compounds that make up the regolith. There are a number of reactions and processes that have been devised which can break apart the regolith compounds and liberate the oxygen. One of the main aspects to all of these processes is the need for heat to be added to the regolith. The most efficient method of achieving this heat addition is by direct heating of the regolith with concentrated solar energy.

The system being evaluated in this analysis utilizes a solar concentrating mirror as a means of providing the thermal energy to heat the regolith and a Stirling heat engine to provide the electrical power to operate the processes involved in the production of oxygen. There is an inherent advantage in overall system efficiency and compact system design by providing direct thermal heating as well as power generation from a single concentrator mirror. Combining the heat processing and electrical generation also enables the system design to be compact. This provides a means of producing a system that can be self-contained and deployed from a single landing vehicle. The ultimate goal of this kind of compact arrangement would be the design of an autonomous, self-contained oxygen production system that can be deployed to the lunar surface and begin oxygen production without the need for human assembly.



Figure 1.—Image of the moon.

## Environment

The moon (shown in fig. 1) is a dry, crater-filled land with no appreciable atmosphere. The temperature difference from the sunlit areas to shadowed areas can exceed 300 K. The surface is covered with a fine powdered regolith made from eons of bombardment by meteors, asteroids and comets. The successful design and operation of a lunar oxygen production system within this harsh environment will require the system to leverage the advantages of the environment (such as abundant solar energy) and minimize the disadvantages (such as temperature extremes). From the solar availability to the amount of removable oxygen in the soil, the capabilities of this system will be based on how well it is adapted to these environmental conditions.

The moon orbits the earth every 27.3 days. It is tidally locked to the Earth and therefore it rotates at the same rate it orbits the Earth. This causes the same side of the moon to face the Earth all of the time. Having the same side continually face the Earth provides an advantage when it comes to communications. A device or system placed on the Earth-facing side of the moon can be in constant communication with Earth without the need for a lunar satellite communication system. Another unique orbital characteristic is its low declination angle of approximately  $1.5^\circ$ . This angle means that there is very little variation in solar elevation throughout the year and little seasonal effect. Because of this, locations at high elevations near the poles would be in constant sunlight throughout the year. The Clementine spacecraft has identified just such a location in 1994 (ref. 1). This location, which is continuously illuminated, is on the rim of the Peary crater at the Moon's north pole. An image of the lunar South Pole is shown in figure 2 (ref. 1). Some additional physical characteristics of the moon are listed in table 1.

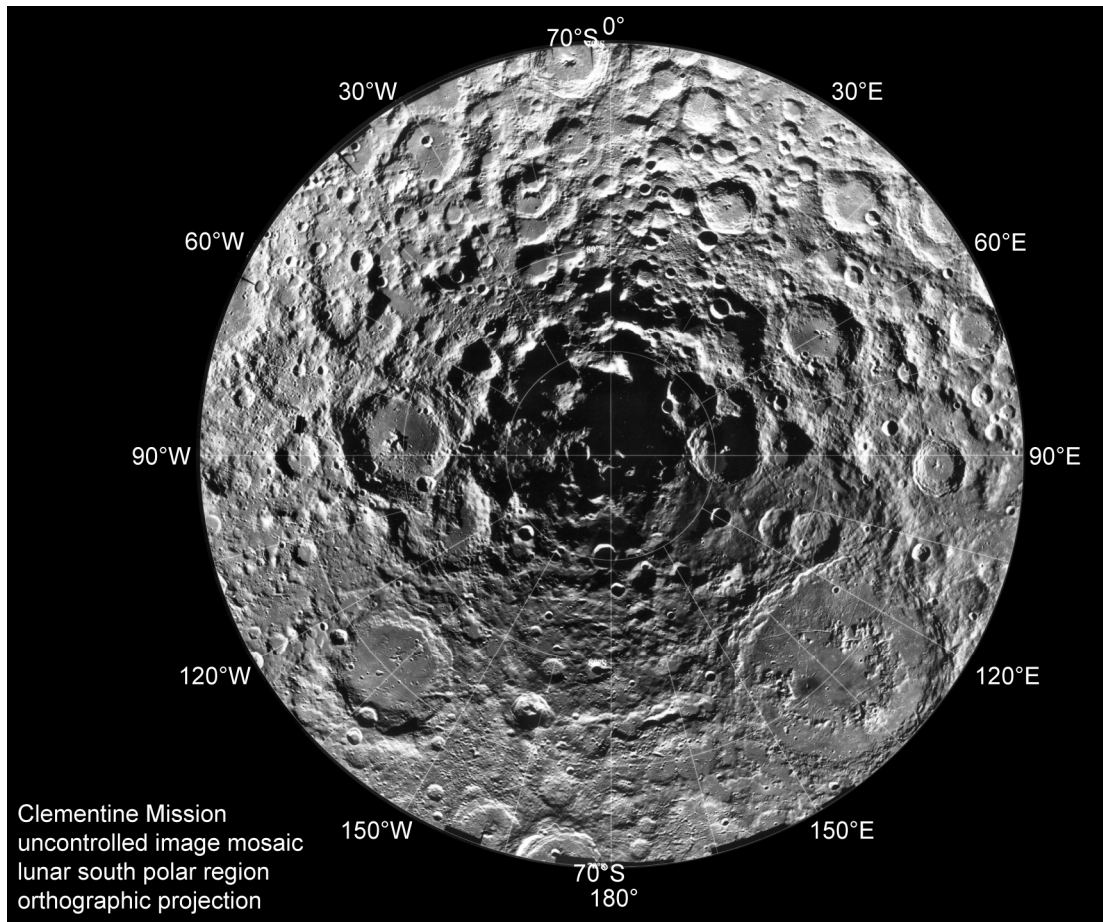


Figure 2.—Lunar south pole.

TABLE 1.—MOON'S PHYSICAL PROPERTIES (REFS. 2 AND 3)

| Parameter                           | Value                  |
|-------------------------------------|------------------------|
| Declination angle                   | 1.5°                   |
| Orbital eccentricity ( $\epsilon$ ) | 0.0549                 |
| Day length                          | 655.7 hours            |
| Distance from Earth                 |                        |
| Perigee                             | 363,300 km             |
| Apogee                              | 405,500 km             |
| Surface gravity (g)                 | 1.623 m/s <sup>2</sup> |
| Surface temperature range           | 102 to 384 K           |

### Surface Characteristics

There are two main types of terrain on the lunar surface, the highlands and the mare. The highlands are the older, brighter regions (as seen from Earth) of the lunar surface and are significantly cratered. The mare are darker regions which are basaltic lava flows. These areas can be seen in the topographic map of the lunar surface shown in figure 3. The blue and purple regions are the lower-lying mare regions while the red, orange and yellow areas are the upper highland regions. The lunar regolith, which covers the surface of the moon, consists of fragments of rocks, minerals and glass spherules formed when meteors or other bodies impacted the surface. The regolith thickness varies greatly with location on the lunar surface. In the mare the thickness can vary between 3 to 16 m whereas in the highlands it is at least 10 m thick (ref. 2). The chemical or mineral composition of the regolith is similar to the underlying bedrock from

which it was derived. There is little mixing of material between the highland and mare regions. The composition of the major materials (greater than 1% of the composition) in each of these regions is given in table 2.

TABLE 2.—LUNAR SURFACE MINERAL COMPOSITION (REFS. 2 AND 4)

| Compound                       | Highland (%) | Mare (%) |
|--------------------------------|--------------|----------|
| SiO <sub>2</sub>               | 44.5         | 41.0     |
| Al <sub>2</sub> O <sub>3</sub> | 26.0         | 12.8     |
| FeO                            | 5.77         | 16.2     |
| CaO                            | 14.9         | 12.4     |
| MgO                            | 8.05         | 9.2      |
| TiO <sub>2</sub>               | -----        | 7.3      |

The regolith is composed of fine grains of the mineral compounds given in table 2. The grain size of the regolith varies but consists mostly of particles less than 1 mm in diameter. This is similar in consistency to silt or fine sand (ref. 2). The average regolith density ( $\rho_r$ ) is approximately 1000 kg/m<sup>3</sup>.

Key compounds in the production of oxygen from lunar material are the iron oxides and titanium dioxides. Figure 4 shows the iron content on the lunar surface and figure 5 shows a map of the titanium content. In both these figures higher concentrations are in red and orange and lower concentrations are in blue.

By looking at figures 3, 4, and 5 it can be seen that the highest concentrations of iron oxide and titanium dioxide (ilmenites, FeTiO<sub>3</sub>) occur in the low-lying mare regions. Within these mare regions of high iron and titanium content, ilmenite will be present in the loose regolith. About two thirds of the ilmenite is in glassy agglutinates and basaltic rock fragments much larger than the common regolith grain size. The average amount of small grain size ilmenite available in the mare regions is approximately 7% by weight (the ratio of mass of regolith to mass of ilmenite,  $R_m$ , is 0.07) and 5% by volume (the ratio of volume of regolith to volume of ilmenite,  $R_v$ , is 0.05) of the regolith (ref. 4).

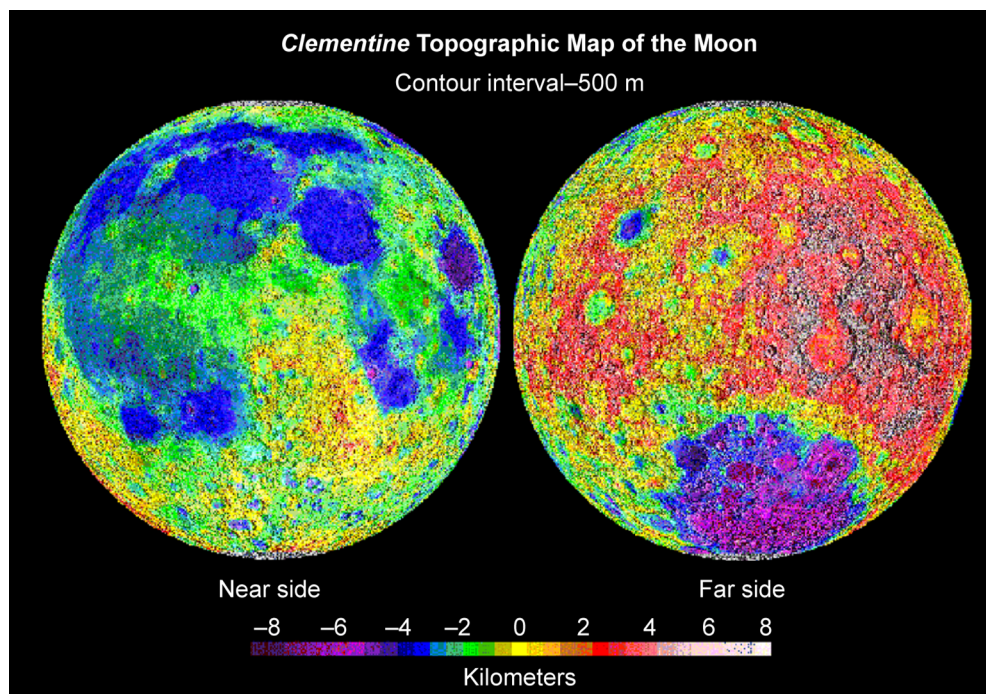


Figure 3.—Lunar topographic map [4].



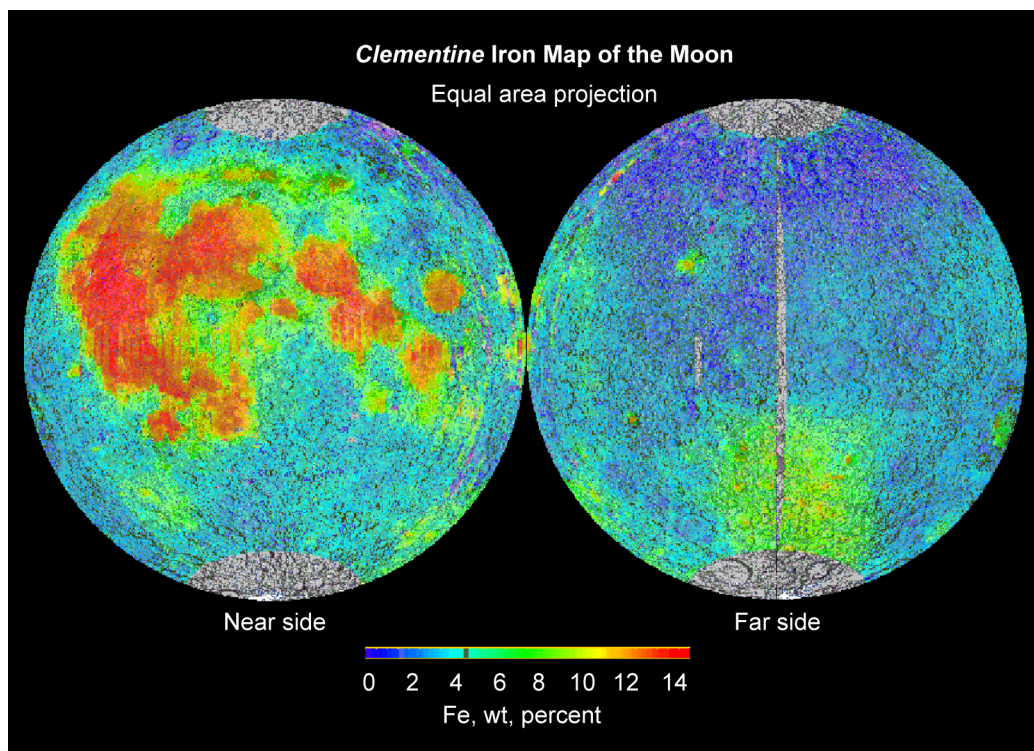


Figure 4.—Iron concentration on the lunar surface [3].

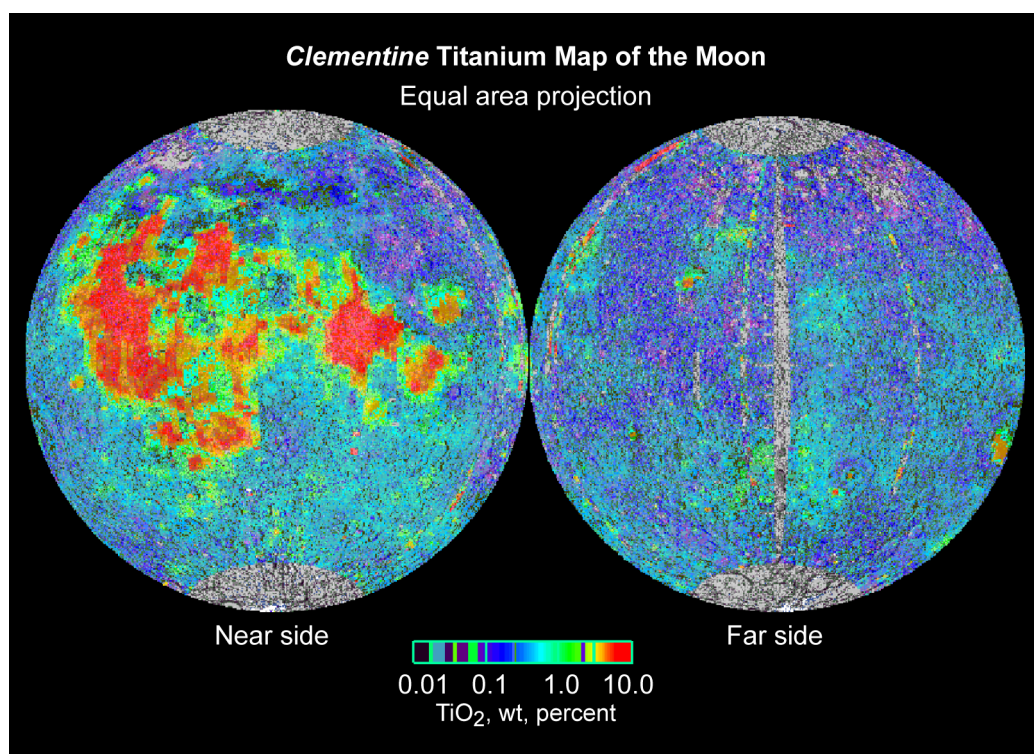


Figure 5.—Titanium concentration on the lunar surface [3].

Based on these percentages the density of ilmenite ( $\rho_i$ ) is approximately 1.4 times that of the regolith or  $1400 \text{ kg/m}^3$ . The thermal conductivity of the fine-grained ilmenite is estimated to be  $0.425 \text{ W/m K}$  which is similar to that of sand (ref. 6). The specific heat of the ilmenite is approximated by that of the mare regolith. The specific heat ( $c_p$ ) as a function of temperature ( $T$ ) is given by equation (1) (ref. 6).

$$c_p = -1848.5 + 1047.41 \log(T_i) \quad [\text{J/kg K}] \quad (1)$$

### Incident Solar Radiation

With the absence of an appreciable atmosphere, the solar intensity at the lunar surface is fairly constant. There is a slight variation throughout the year due to the Earth's orbital eccentricity about the Sun. The mean solar intensity ( $I_m$ ) at Earth's orbital location is  $1353 \text{ W/m}^2$  (ref. 7). The variation in Earth's orbital radius ( $r_{orb}$ ) from the mean orbital radius ( $r_{orb m}$ , which has a value of  $1.496 \text{E}8 \text{ km}$ ) is represented by the eccentricity ( $\epsilon$ ) of Earth's orbit that has a value of 0.017. The actual solar flux (or intensity,  $I$ ) in  $\text{W/m}^2$  for a specific day of the year is determined by equations (2) and (3). This variation in solar intensity throughout the year is shown in figure 6.

$$I = I_m \left( r_{orb m}^2 / r_{orb}^2 \right) \quad (2)$$

$$r_{orb} = (1 - \epsilon^2) / (1 + \cos(\alpha)) \quad (3)$$

The day angle ( $\alpha$ ) used in equation (3) is defined as  $0^\circ$  on January 4<sup>th</sup> (perihelion of Earth's orbit) and increases by  $0.98^\circ$  per day. The solar output varies from approximately  $1400 \text{ W/m}^2$  (on January 4<sup>th</sup>) to  $1308 \text{ W/m}^2$  (on July 9<sup>th</sup>). The variation on the solar intensity at the lunar surface due to the orbit of the moon around the earth is very slight. The distance between the moon and earth varies between  $360,300 \text{ km}$  (at perigee) to  $405,500$  (at apogee). The greatest effect on solar intensity produced by the Moon's orbit about the Earth is a decrease of about  $0.56\%$  ( $\sim 6 \text{ W/m}^2$ ) in the solar intensity at the Lunar surface. This small change in intensity will vary as the moon orbits the Earth or in other words throughout the lunar day. Therefore it was assumed to be negligible and the solar intensity at Earth orbit was utilized in the subsequent analysis.

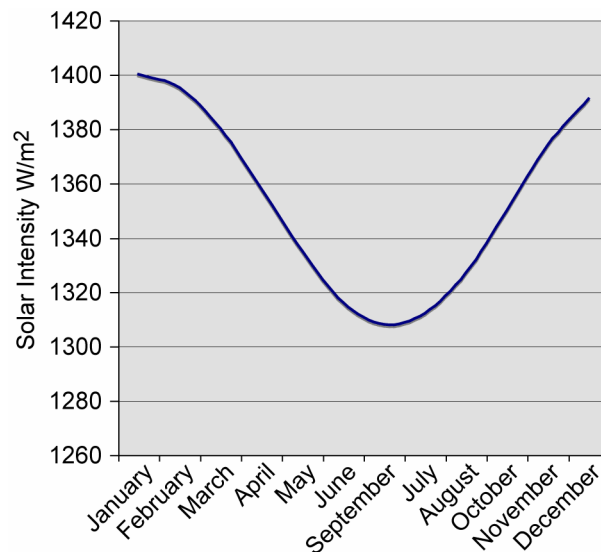


Figure 6.—Variation in solar intensity at earth orbital location.

## Oxygen Production

There are a number of potential methods for extracting oxygen from the lunar soil. The method selected for this analysis is the hydrogen reduction of ilmenite. This is one of the more commonly proposed methods of oxygen production from Lunar regolith. It is a fairly simple method that can be accomplished with present day materials. Because the reaction takes place at a relatively low temperature, below the melting point of the soil, the material compatibility and corrosiveness are not significant issues. The process utilizes hydrogen gas that will need to be supplied from Earth. However, the gas is recoverable in the oxygen generation process. Therefore after the initial supply only make-up gas will be needed to account for that which is not recovered or lost through leaking. Another advantage of this type of production is that it can utilize the surface regolith in areas that have a high iron and titanium content. This eliminates the need for mining or processing rocks which are both very power intensive. For an initial oxygen production capability, and as a means of demonstrating the oxygen production technology, being able to directly utilize the regolith is a significant advantage.

The hydrogen reduction of ilmenite is a two-step process represented by the reactions given in equations (4) and (5) (ref. 4). The first step in the process is the reduction of the ilmenite to iron, titanium dioxide and water. The second step is the electrolysis of the water to form hydrogen and oxygen.



Both the hydrogen and oxygen that are produced in the process can be captured. The oxygen will be stored for use and the hydrogen will be reused in the process. The reduction process is performed in a fluidized bed reactor and the electrolysis is performed with an electrolyzer. The main components of the process include the following:

- Scoop and Transport Belt for Regolith
- Large Particle Removal Screen
- Magnetic Ilmenite Separator
- Hydrogen Supplied Fluidized Bed Reactor
- Electrolyzer
- Solar Dynamic Mirror
- Sterling Heat Engines

A diagram of the process is given in figure 7. The process requires the ilmenite to remain at an elevated temperature ( $T_i$ ) of 1273 K for approximately 1 hour. An additional benefit to the heating of the ilmenite is the liberation of hydrogen. Hydrogen is present in mature lunar regolith due to exposure to the solar wind over long periods of time. The finer the particle grains the larger the amount of hydrogen it will have trapped. This hydrogen content will range from 0.1 to 0.2 kg/m<sup>3</sup> of regolith. Since this hydrogen content is dependent on grain size not material content it is reasonable to assume the concentration in the ilmenite is the same as that in the overall regolith. Therefore, as the ilmenite is heated the hydrogen bonded to it will be released. It is estimated that at 900 °C all of the hydrogen trapped with the ilmenite will be released.

This released hydrogen will be utilized in the reduction of the ilmenite and will add to the overall hydrogen already in the system. It can be considered a source of makeup hydrogen to help offset any losses of hydrogen from the system.

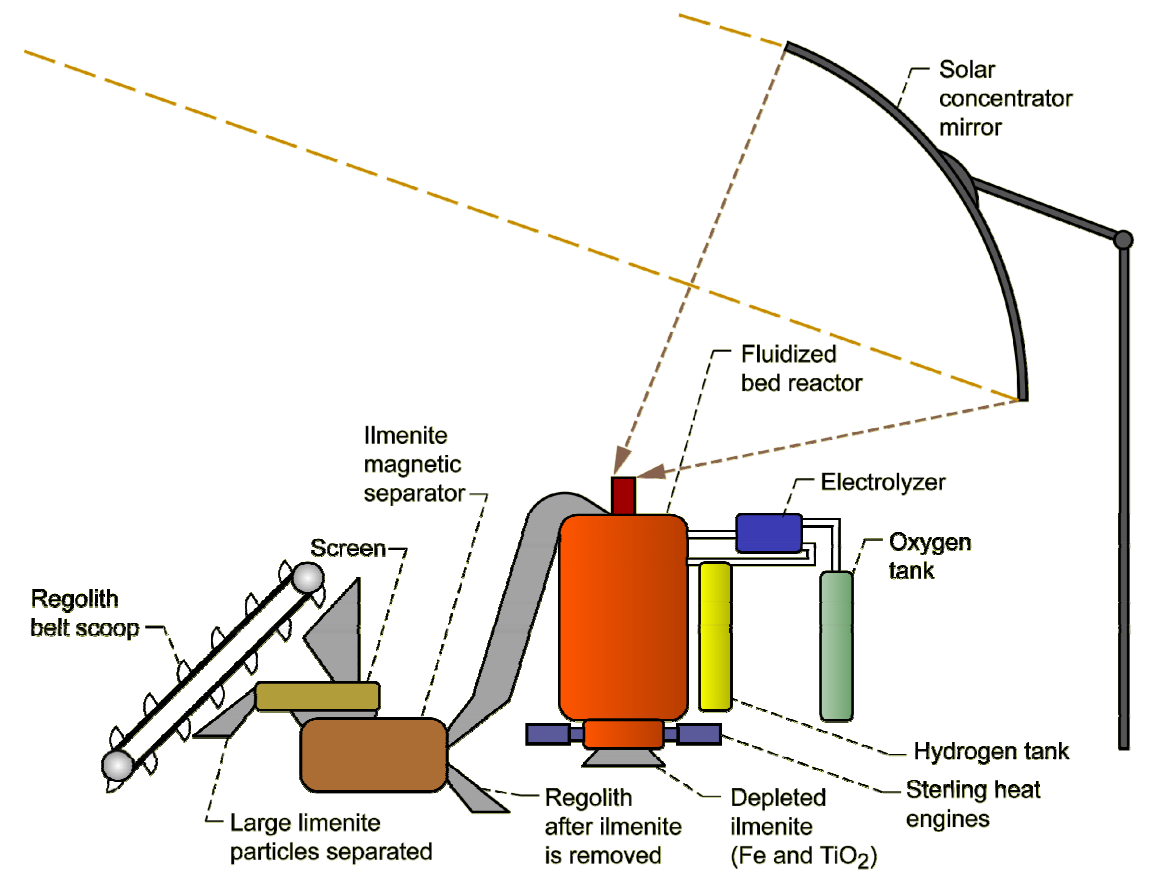


Figure 7.—Oxygen production process and component.

The sequence for the process illustrated in figure 7 consists of the following:

- Scooping the regolith and transporting it to the screen.
- The larger regolith particles (greater than 1 mm in diameter) are separated using a vibrating screen.
- The regolith is then transported to a magnetic separator where the ilmenite is separated from the regolith.
- The ilmenite is transported to the fluidized bed reactor
- In the reactor the ilmenite is heated while hydrogen gas is circulated (it is maintained at 1273 K for 1 hour).
- The water vapor output is passed through an electrolyzer where it is separated into hydrogen and oxygen gas.
- The hydrogen gas is returned to the reactor and the oxygen is stored

## Analysis

An analysis was set up to evaluate the sizing of the system shown in figure 7 for various rates of oxygen production. The sizing was based on scaling the solar dynamic system to provide sufficient heat to run the ilmenite reduction reaction as well as provide electrical power for operating all of the other process involved with the oxygen production. The electrical power is produced by a series of Stirling heat



engines. To perform the sizing analysis an energy balance between the heat provided by the concentrator mirror and the requirements of the various components both thermally and electrically had to be made. Each of the components' thermal or electrical energy consumption has to be determined and scaled with the amount of regolith and or ilmenite being processed. Since the process involves moving the material around, the height and rate of movement is needed in order to determine the energy consumption. These values can be varied to determine what effect they have on the system sizing and production rate.

The rate of ilmenite going into the reactor sets the rates for all of the other processes. This rate can be represented by the fraction of the reactor volume that is replenished each hour,  $\dot{V}_{ir}$ . This quantity will have a value between 0 and 1. Establishing the replacement rate of the ilmenite in the reactor also sets the volume and mass flow requirements for all the other process in the system. From this, the mass rate at which the regolith must be acquired from the surface ( $\dot{M}_r$  in kilograms per hour) can be determined. This rate, which is based on the total volume of ilmenite in the fluidized bed reactor, is given by equation (6). The reactor is assumed to be cylindrical. The diameter ( $d_r$ ) and height ( $h_r$ ) can be adjusted to increase or decrease the overall volume of ilmenite processed.

$$\dot{M}_r = \frac{\rho_i \dot{V}_{ir} \pi d_r^2 h_r}{4 R_m} \quad (6)$$

The rate at which the regolith is taken from the surface sets the power required to scoop the regolith ( $P_{rs}$ ) and transport it to the screen ( $P_{rl}$ ). These quantities are given in equations (7) and (8) respectively. The power to scoop the regolith is dependent on the distance the belt scoops travel in the regolith ( $d_{rs}$ , assumed to be 1 m) and the coefficient of friction of the regolith ( $\mu_r$ ). The regolith coefficient of friction was assumed to be 0.4, which is similar to that of sand. The power to lift the regolith is dependent on the height it is raised. This height is assumed to be the height of the reactor plus the height the reactor is above the surface ( $h_{rs}$ , assumed to be 1 m). The electric motor efficiency ( $\eta_{em}$ ) to drive the scoop and lift the regolith is assumed to be 90%.

$$P_{rs} = \frac{\mu_r d_{rs} \dot{M}_r g}{3600 \eta_{em}} \quad (7)$$

$$P_{rl} = \frac{(h_r + h_{rs}) \dot{M}_r g}{3600 \eta_{em}} \quad (8)$$

Once the regolith is picked up off of the surface, the first step is to screen out the larger particles; those greater than a specific size are removed. This screening is necessary for the efficient operation of the fluidized bed reactor. The maximum particle size ( $d_s$ ) and subsequent screen opening that allows for efficient fluidization is calculated in equation (9) (ref. 4). This equation has to be solved iteratively for the maximum particle size. It factors in a number of parameters for the operation of the fluidized bed reactor. These include the porosity of the fluidized bed ( $\epsilon_p$ , estimated to be 0.5) and the hydrogen gas velocity within the reactor ( $U_{H_2}$ , estimated to be 0.3 m/s). Details on the hydrogen gas properties and the ilmenite are also required. These include the hydrogen gas density ( $\rho_{H_2}$ , given in eq. (10)), hydrogen viscosity ( $\mu_{H_2}$ , estimated to be  $2.37 \times 10^{-5}$  kg/m-s (ref. 4)), ilmenite particle shape factor ( $\phi$ , estimated to be that of sand, 0.83) and the ilmenite particle density ( $\rho_{ip}$ , estimated to be  $4790 \text{ kg/m}^3$ ). The ilmenite particle density is greater than that of the ilmenite in the soil. This is because the density of the ilmenite in the soil takes into account any spacing between the particles where as the particle density is that of the material that makes up each particle.

$$\frac{150\rho_{H2}(1-\varepsilon_p)U_{H2}}{\varphi^2\varepsilon_p^3\mu_{H2}} = \frac{g\rho_{H2}(\rho_{ip}-\rho_{H2})}{\mu_{H2}^2}d_i^2 - \frac{1.75\rho_{H2}^2U_{H2}^2}{\varphi\varepsilon_p^3\mu_{H2}^2}d_i \quad (9)$$

The hydrogen gas density is based on the ideal gas law (pressure ( $P_{H2}$ ) in Pascal, temperature ( $T_i$ ) in degrees Kelvin and the gas constant for hydrogen ( $R_{H2}$ ), 4157 Nm/kg K) with a compressibility factor ( $Z_{H2}$ ) for the hydrogen gas (ref. 8).

$$\rho_{H2} = \frac{P_{H2}}{Z_{H2}R_{H2}T_i} \quad (10)$$

$$Z_{H2} = 0.99704 + 6.4149E - 9P_{H2} \quad (11)$$

The screening method selected for this analysis is a vibratory screen. A vibratory screening process is fairly simple. A screen with a specified mesh or opening size is vibrated as the regolith is pored onto it. The material that is less then the opening size will fall through to the next stage in the process whereas the material larger then the openings will be moved across the screen surface and discharged off one end of the screen and returned to the lunar surface. The power required to operate the vibratory screener ( $P_{vs}$ ) is given by equation (12) (ref. 4).

$$P_{vs} = \frac{0.45\dot{M}_r}{507.72d_i + 49.91\sqrt{d_i}} \quad (12)$$

The screening process will eliminate a portion of the regolith that was collected. The fraction of the regolith that will make it through the screen will depend on the desired maximum particle size determined by equation (9). The particle size distribution ( $n_r$ ) of the regolith in meters is given by equation (13). This equation is a curve fit representation of data (ref. 4) on the percent concentration of particle size within the regolith. The particle size distribution along with the corresponding curve fit is plotted in figure 8.

$$n_r = \frac{d_i - 9.4008E - 6}{d_i + 8.0419E - 5} \quad (13)$$

The next step in the process is to separate out the ilmenite from the regolith. For a smaller scale oxygen production plant the use of a permanent or electro-magnet separator is preferred. This type of separator minimizes the power requirements compared to an induced magnetic roll separator or an electrostatic separator. This type of separator consists of a drum with alternating magnetic poles along its surface. Material is dropped over the drum as it rotates. Magnetic material will adhere to the surface where it is scrapped off and captured. Nonmagnetic material will drop out of the bottom of the separator (ref. 9). The power consumed by the separator ( $P_{ms}$ ) in watts is given by equation (14) (ref. 4).

$$P_{ms} = 0.196n_r\dot{M}_r \quad (14)$$

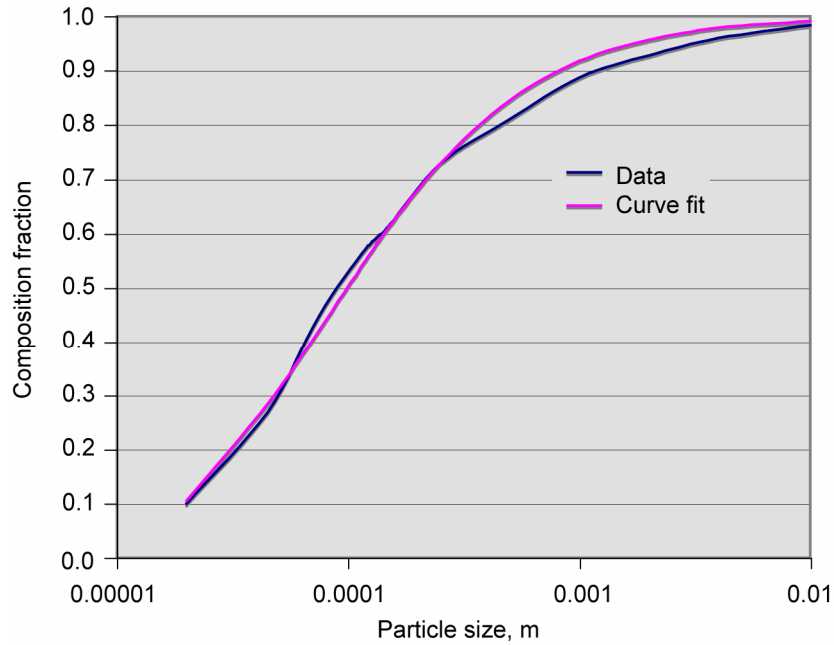


Figure 8.—Particle size distribution in the regolith.

The separated ilmenite has to now be lifted into the fluidized bed reactor. This distance is assumed to be the height of the reactor plus the distance the reactor is above the surface. The power required to lift the ilmenite ( $P_{il}$ ) is given by equation (15). Where the mass flow of ilmenite in kilograms per hour is given by equation (16). It is assumed that the separation process is 90% efficient ( $\eta_s$ ). Therefore 90% of the mass flow given by equation (15) will be ilmenite. The remainder will be other materials that will not contribute to the reaction although it will go through the complete heating process.

$$P_{il} = \frac{(h_r + h_{rs})\dot{M}_i g}{3600\eta_{em}} \quad (15)$$

$$\dot{M}_i = n_r R_m \dot{M}_r \quad (16)$$

Once the ilmenite enters the fluidized bed reactor it is heated to 1273 K and hydrogen gas is circulated through it. The energy to heat the soil comes from the solar concentrator. The concentrated solar radiation is focused onto a heat receiver. This heat receiver then conducts the heat into the reactor chamber where it is distributed throughout the chamber to heat the ilmenite. It is assumed that the ilmenite will heat uniformly once it is placed in the reactor. As the ilmenite passes from the top of the reactor to the bottom it is slowly heated. The selected rate, at which the volume of ilmenite in the reactor is replaced, given previously as  $\dot{V}_i$ , sets the amount of heat needed to heat the soil. The ilmenite must be brought up to temperature and remain at temperature for a specified period of time ( $t_t$ , in hours) in order for the reduction reaction (given by eq. (4)) to take place. The time available to heat the ilmenite ( $t_h$ , in hours) is given by equation (17). From this equation it should be observed that there is an inherent limit on the rate at which the ilmenite is replaced and the duration at which it must be at temperature. This is because the time available to heat the ilmenite must be greater than zero.

$$t_h = \left( \frac{1}{\dot{V}_{ir}} - t_t \right) \text{ where } \dot{V}_{ir} t_t < 1 \quad (17)$$

The thermal power required to heat the ilmenite ( $Q_{hi}$ ), given by equation (18), is dependent on this available heating time, the volume of ilmenite being heated and the initial ilmenite properties. It is assumed that the ilmenite is initially at the illuminated surface temperature ( $T_{io}$ ) of 384 K.

$$Q_{hi} = \frac{\rho_i c_p (T_i - T_{io}) \pi d_r^2 h_r (1 - t_t \dot{V}_{ir})}{14,400 t_h} \quad (18)$$

The ilmenite will lose heat to the surroundings ( $Q_{ls}$ ) as it is being heated. To minimize this heat loss, the outside of the reactor vessel can be insulated with multilayer insulation. Because of the vacuum conditions at the lunar surface, radiation heat transfer is the only mechanism in which the reactor vessel will transfer heat to the surroundings. Therefore multiple layers of a low emissivity ( $\epsilon_i$ ) material (such as polished nickel,  $\epsilon_i = 0.17$ ) that are closely layered will provide very good insulation. The greater the number of layers ( $n_l$ ) and the smaller the spacing between the layers ( $d_{il}$ ), the less the heat loss to the surroundings will be. The heat loss to the surroundings (at a sink temperature  $T_s = 270$  K) from the insulated reactor vessel can be calculated from equation (19) where the Stefan-Boltzman constant ( $\sigma$ ) has a value of  $5.67\text{E}-8$  W/m<sup>2</sup> K. If the reactor is constructed of a material different than that of the insulation it will have a different emissivity ( $\epsilon_r$ , such as chromium  $\epsilon_r = 0.14$ ).

$$Q_{ls} = \frac{\pi (d_r + n_l d_{il}) h_r \sigma (T_i^4 - T_s^4)}{\left( \frac{1}{\epsilon_c} + \frac{2n_l}{\epsilon_i} - n_l + 1 \right)} \quad (19)$$

In addition to the heat required to bring the ilmenite to the desired temperature and the loss of heat to the surroundings, the hydrogen reduction reaction itself will absorb heat from the system. The amount of heat consumed ( $Q_r$ ) due to the heat of reaction ( $H_r$ ) is given by equation (20). The heat of reaction for the hydrogen reduction of ilmenite is given as 294, 000 J/kg (ref. 4).

$$Q_r = \frac{H_r \eta_s \dot{M}_i}{3600} \quad (20)$$

The last power-consuming component of the system is the electrolyzer. The electrolyzer power requirement will depend on the amount of water that needs to be electrolyzed. The rate of water production ( $\dot{M}_w$ ) is based on the ratio of the molecular weights of the reactant and product of interest, water. The rate of water production in kilograms per hour is given by equation (21). Subsequently the rate of oxygen production ( $\dot{M}_o$ ) can then be determined, which is given by equation (22).

$$\dot{M}_w = \eta_s \dot{M}_i \frac{18}{308} \quad (21)$$

$$\dot{M}_o = \dot{M}_w \frac{16}{18} \quad (22)$$

The power required by the electrolyzer to separate the water into hydrogen and oxygen can be calculated based on the theoretical power needed to break apart water (3520 W/kg/hr), the efficiency of the electrolyzer ( $\eta_e$ ) and the rate of water flow to the electrolyzer.

$$P_e = 3520 \frac{\dot{M}_w}{\eta_e} \quad (23)$$

The electrical power to operate the scoop and belt motors, run the magnetic separator and vibratory separator and operate the electrolyzer is provided by a number of Stirling heat engines. The required power output ( $P_{se}$ ) of these engines is given by equation (24) and the subsequent heat input to the system to run the engines is given by equation (25). This heat input is based on the conversion efficiency of the Stirling engine ( $\eta_{se}$ ) that is estimated to be 35%.

$$P_{se} = P_{rs} + P_{rl} + P_{vs} + P_{ms} + P_{il} + P_e \quad (24)$$

$$Q_{se} = \frac{P_{se}}{\eta_{se}} \quad (25)$$

The total thermal power output needed and the corresponding diameter of the solar concentrator mirror ( $d_m$ ) can now be calculated. The total thermal power ( $Q_{total}$ ) output is given by equation (26). The required solar concentrator diameter is given by equation (27) and assumes it is circular in shape. The diameter is dependent on the mirror reflectance efficiency ( $\eta_m$ ) and the efficiency of the heat receiver ( $\eta_r$ ).

$$Q_{total} = Q_{se} + Q_r + Q_{ls} + Q_{hi} \quad (26)$$

$$d_m = \sqrt{\frac{4Q_{total}}{\pi\eta_m\eta_r I}} \quad (27)$$

## Results

Utilizing the analysis outlined in the previous section, data was produced on the achievable oxygen production rate for various size systems. Initially a baseline case was produced that represents the initial design and operation point for the system. The baseline assumptions that were used to generate this case are given in table 3. These assumptions represent the best estimates of the performance for the various components as well as an initial sizing that is within the scope of a demonstration oxygen production system. The system sizing and performance results for the baseline system are given in table 4 and a breakdown of the thermal and electrical power requirements are shown in figures 9 and 10 respectively.

From figure 9 it can be seen that the main thermal requirement for the system is for the production of electricity. Of the electricity that is produced, shown in figure 10, almost all of it is used by the electrolyzer in breaking apart the water to produce oxygen.

TABLE 3.—BASELINE ANALYSIS ASSUMPTIONS

| Variable   | Value                       |
|--|-----------------------------|
| Fraction of the fluidized bed reactor that is replenished each hour ( $\dot{V}_{ir}$ ) | 0.1 (1/hr)                  |
| Reactor diameter ( $d_r$ )   | 0.5 m                       |
| Reactor height ( $h_r$ )   | 0.5 m                       |
| Operational date, day angle ( $\alpha$ )   | July 9 <sup>th</sup> , 180° |
| Distance the scoop is in the Regolith ( $d_{rs}$ )                                     | 1 m                         |
| Height the fluidized bed reactor is above the surface ( $h_{rs}$ )                     | 1 m                         |
| Porosity of the fluidized bed ( $\epsilon_p$ )   | 0.5                         |
| Hydrogen velocity through the fluidized bed ( $U_{H_2}$ )                              | 0.3 m/s                     |
| Hydrogen pressure within the fluidized bed ( $P_{H_2}$ )                               | 1E6 Pa (10 atm)             |
| Ilmenite hydrogen reduction reaction temperature ( $T_i$ )                             | 1273 K                      |
| Time ilmenite is held at reaction temperature ( $t_t$ )                                | 1 hr                        |
| Number of layers of MLI insulation ( $n_l$ )   | 50                          |
| Sink temperature of surroundings ( $T_s$ )   | 270 K                       |
| Electric motor efficiency ( $\eta_{em}$ )  | 0.90                        |
| Ilmenite separation efficiency ( $\eta_s$ )  | 0.90                        |
| Electrolyzer efficiency  | 0.72                        |
| Stirling engine efficiency   | 0.35                        |
| Concentrator mirror efficiency   | 0.90                        |
| Heat receiver efficiency   | 0.90                        |

TABLE 4.—BASELINE SIZING AND PERFORMANCE RESULTS

| Quantity                          | Value                         |
|-----------------------------------|-------------------------------|
| Available solar intensity         | 1301 W/m <sup>2</sup>         |
| Total thermal power required      | 15,241 W                      |
| Total electrical power required   | 3,272 W                       |
| Concentrator mirror area/diameter | 14.38 m <sup>2</sup> / 4.28 m |
| Reactor volume                    | 0.098 m <sup>3</sup>          |
| Maximum particle size             | 0.842 mm                      |
| Total mass of hydrogen required   | 0.73 kg                       |
| Water production rate             | 0.653 kg/hr                   |
| Oxygen production rate            | 0.58 kg/hr                    |

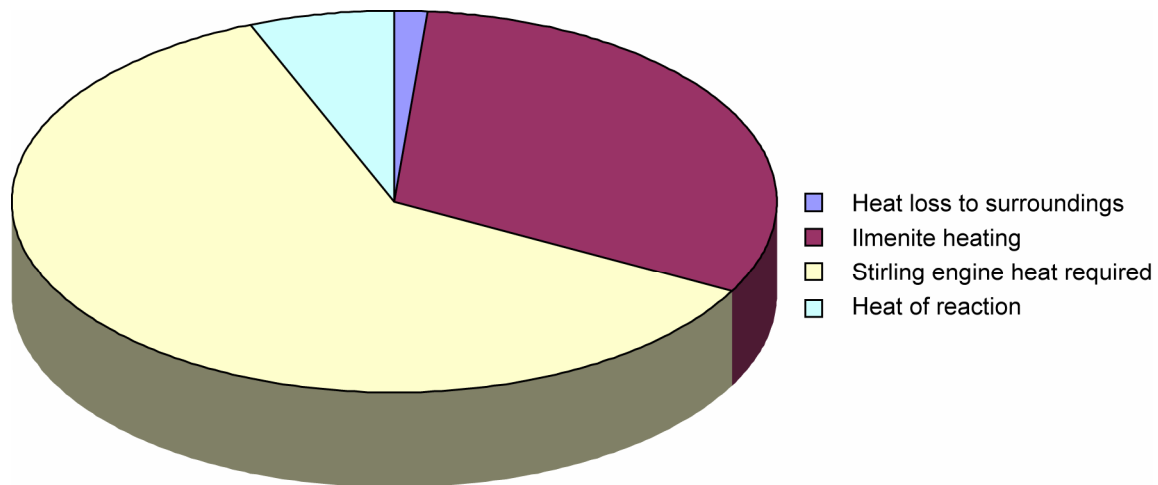


Figure 9.—Breakdown of thermal power requirements.

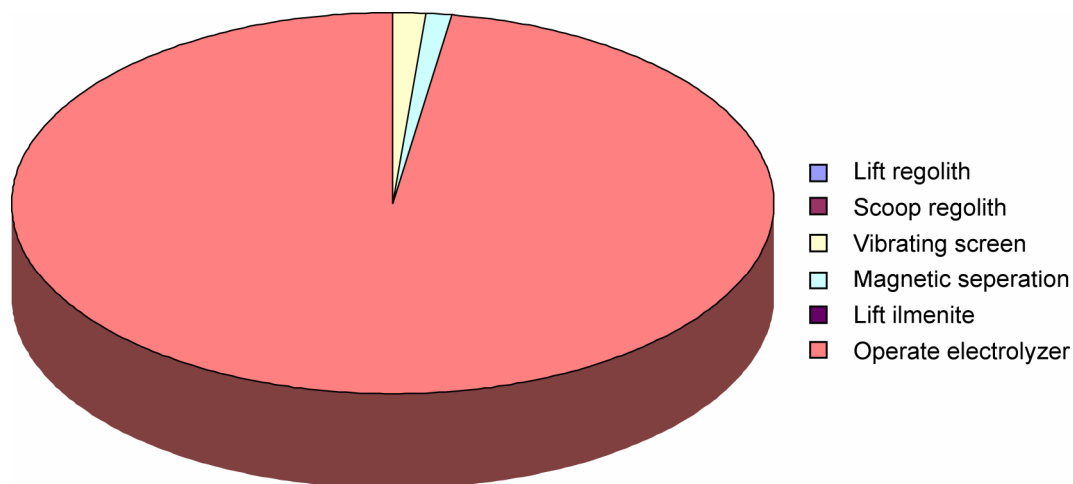


Figure 10.—Breakdown of electrical power requirements.

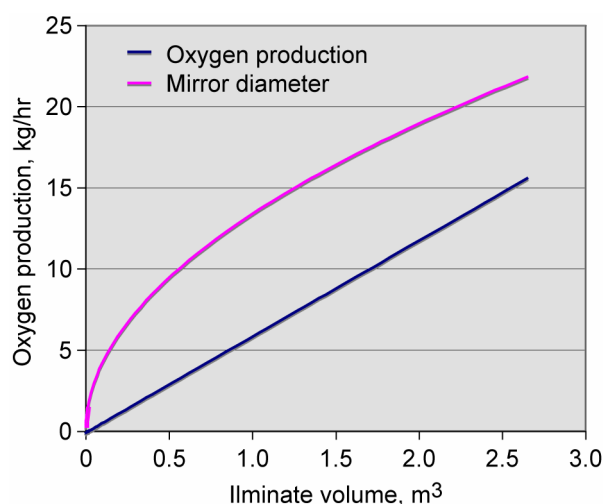


Figure 11.—Oxygen production rate and mirror diameter for various volume reactors.

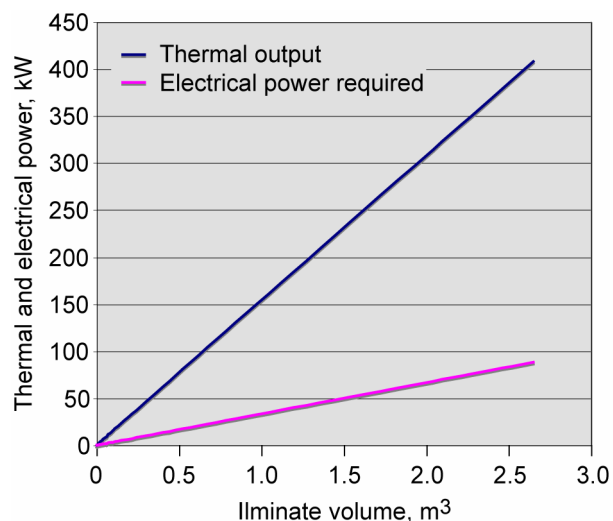


Figure 12.—Thermal and electrical output requirements for various volume reactors.

From this initial case, variations were made to some of the variables to determine what impact they have on the system sizing and output. The container volume was varied from near zero to 2.5 m<sup>3</sup>. The remaining variables, given in table 3, were not changed. The corresponding oxygen production rate and mirror diameter are plotted in figure 11 and the required thermal and electrical output is plotted in figure 12. From these figures it can be seen that there is a linear increase in oxygen production with the increase in reactor volume. This should be expected since the amount of oxygen is directly proportional to the volume of ilmenite being reduced. The thermal and electrical power requirements also increase linearly with the reactor volume.

Another means of changing the rate of oxygen production is to vary the rate at which the ilmenite is replaced in the reactor. For the baseline case this rate was set at 10% of the container volume per hour. By varying this rate the amount of oxygen produced will change as well as the required thermal power and correspondingly mirror size. The oxygen production rate and the required mirror diameter as a function of the fraction of the ilmenite in the reactor replaced each hour is shown in figure 13. Figure 14 shows the thermal and electrical power required as a function of the fraction of ilmenite replaced in the reactor each hour.

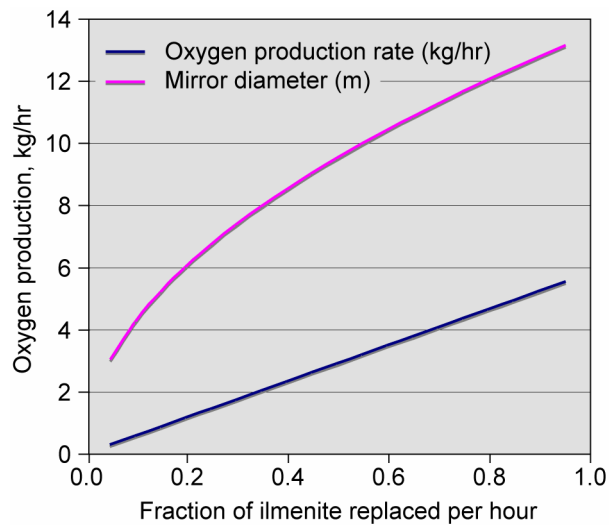


Figure 13.—Oxygen production rate and mirror diameter for different rates of ilmenite replacement.

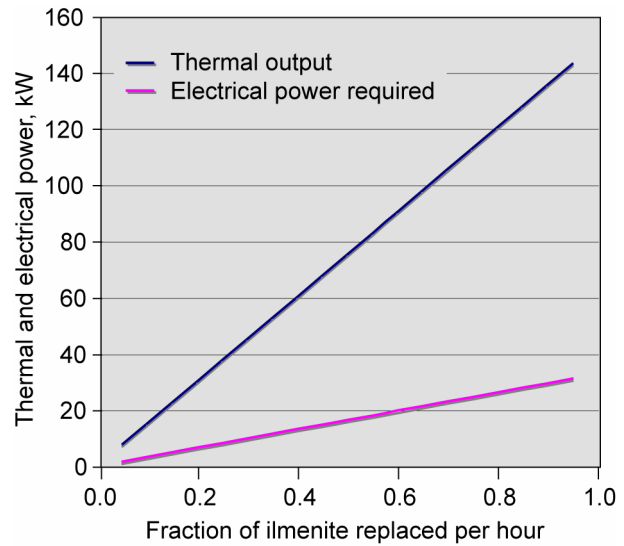


Figure 14.—Thermal and electrical output requirements for different rates of ilmenite replacement.

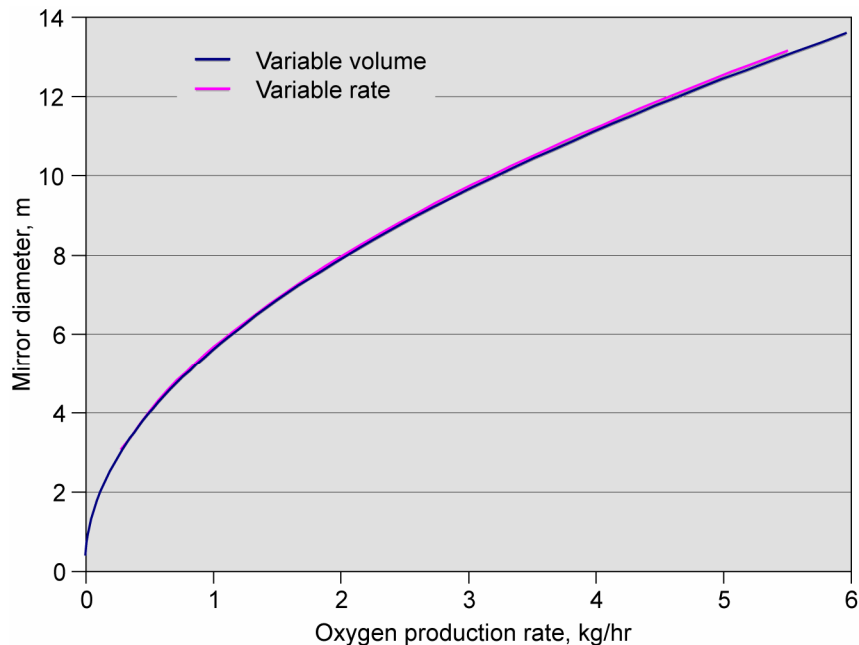


Figure 15.—Mirror size as a function of oxygen production rate for both variable volume and rate.

Using the data produced a direct comparison between the oxygen production rate and the mirror diameter can be made. This comparison is plotted in figure 15 for both the variable volume and the variable rate cases. From this figure it can be seen that there for a given oxygen production rate the required mirror diameter is basically the same between the variable volume or rate cases. Therefore higher production rates can be achieved either through increasing the volume of the reactor or by increasing the rate at which the ilmenite is processed through the reactor. In either case, for a given rate of oxygen production the effect on the thermal and power system sizing is the same.



## Conclusion

The results of this initial sizing analysis show that a useable amount of oxygen can be produced from a reasonable sized solar dynamic system. The results of the baseline system produced just under 0.6 kg of oxygen per hour with a mirror size of less than 5 m diameter. For a full 14 day mission, where the production plant is in continuous sunlight, approximately 195 kg of oxygen would be produced. This translates into a yearly production rate of approximately 2300 kg of oxygen. The system size should also enable it to be packaged into a single launch vehicle providing a system configuration that can be autonomously deployed and operated. If greater oxygen production rates are required the system can be scaled up, requiring a larger mirror size for operation. Another alternative is to consider these oxygen production systems as modular. If an increased rate of production is needed then two or more systems can be utilized.

As more detail is incorporated into the various components that make up the system, the sizing and oxygen production rates can change. However, the results produced by this analysis should be representative of the system's potential. The results show that a solar dynamic/Stirling heat engine system is an ideal candidate for powering a lunar oxygen production facility. The system provides for an efficient, compact design that can be designed as an integrated stand-alone unit. This would enable the system to be utilized for a number of different applications from a main base to a remote camp. It also can provide a basis for a standardized, modular oxygen production system design.

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